

**SEISMIC HAZARD ZONE REPORT FOR THE
SAN LEANDRO 7.5-MINUTE QUADRANGLE,
ALAMEDA COUNTY, CALIFORNIA**

2003



DEPARTMENT OF CONSERVATION
California Geological Survey

THE RESOURCES AGENCY
MARY D. NICHOLS
SECRETARY FOR RESOURCES

STATE OF CALIFORNIA
GRAY DAVIS
GOVERNOR

DEPARTMENT OF CONSERVATION
DARRYL YOUNG
DIRECTOR



CALIFORNIA GEOLOGICAL SURVEY
JAMES F. DAVIS, *STATE GEOLOGIST*

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SEISMIC HAZARD ZONE REPORT 078

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EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the on-land portion of the San Leandro 7.5-Minute Quadrangle, Alameda County, California. The map displays the boundaries of zones of required investigation for liquefaction and earthquake-induced landslides over an area of approximately 32 square miles at a scale of 1 inch = 2,000 feet.

Although the quadrangle covers approximately 60 square miles in Alameda and San Mateo counties, about half of the area is occupied by San Francisco Bay. All of the land in the quadrangle is within Alameda County. Parts of the cities of Oakland, Alameda, San Leandro and Hayward occupy about 90 percent of this region. The remainder includes San Lorenzo, which is part of unincorporated Alameda County. Gently sloping alluviated plains and low-lying shoreline regions bordering the San Francisco Bay make up most of the onshore region. The northeastern corner of the quadrangle contains a portion of the moderately to steeply sloping East Bay Hills, which rise to just over 720 feet at the highest point. Major streams in the area are San Leandro Creek and San Lorenzo Creek. Several short, steep ravines have been cut perpendicular to the trace of the Hayward Fault, which, in places, forms a small linear valley parallel to the base of the hills. Most of the alluvial plains within the quadrangle have been developed for residential and commercial uses except for some areas along the margin of the bay. More than half of the hillside region also has been developed for residential use. Major highways in the map area are Interstate highways 880 and 580.

The map is prepared by employing geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information considered includes topography, surface and subsurface geology, borehole data, historical ground-water levels, existing landslide features, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. The shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years.

In the San Leandro Quadrangle most of the flatlands are within the liquefaction zone of required investigation. The earthquake-induced landslide hazard zone covers approximately two percent of the land area of the San Leandro Quadrangle. Although only about seven percent of the land area of the quadrangle is hilly, nearly 24 percent of the hilly area is included in the landslide hazard zone.

How to view or obtain the map

Seismic Hazard Zone Maps, Seismic Hazard Zone Reports and additional information on seismic hazard zone mapping in California are available on the California Geological Survey's Internet page: <http://www.consrv.ca.gov/CGS/index.htm>

Paper copies of Official Seismic Hazard Zone Maps, released by CGS, which depict zones of required investigation for liquefaction and/or earthquake-induced landslides, are available for purchase from:

BPS Reprographic Services
149 Second Street
San Francisco, California 94105
(415) 512-6550

Seismic Hazard Zone Reports (SHZR) summarize the development of the hazard zone map for each area and contain background documentation for use by site investigators and local government reviewers. These reports are available for reference at CGS offices in Sacramento, San Francisco, and Los Angeles. **NOTE: The reports are not available through BPS Reprographic Services.**

INTRODUCTION

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate seismic hazard zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold development permits for a site within a zone until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans. The Act also requires sellers (and their agents) of real property within a mapped hazard zone to disclose at the time of sale that the property lies within such a zone. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is on the Internet at <http://gmw.consrv.ca.gov/shmp/SHMPsp117.asp>

The Act directs SMGB to appoint and consult with the Seismic Hazards Mapping Act Advisory Committee (SHMAAC) in developing criteria for the preparation of the seismic hazard zone maps. SHMAAC consists of geologists, seismologists, civil and structural engineers, representatives of city and county governments, the state insurance commissioner and the insurance industry. In 1991 SMGB adopted initial criteria for delineating seismic hazard zones to promote uniform and effective statewide implementation of the Act. These initial criteria provide detailed standards for mapping regional liquefaction hazards. The Act also directed CGS to develop a set of probabilistic seismic maps for California and to research methods that might be appropriate for mapping earthquake-induced landslide hazards.

In 1996, working groups established by SHMAAC reviewed the prototype maps and the techniques used to create them. The reviews resulted in recommendations that 1) the process for zoning liquefaction hazards remain unchanged and 2) earthquake-induced landslide zones be delineated using a modified Newmark analysis.

This Seismic Hazard Zone Report summarizes the development of the hazard zone map. The process of zoning for liquefaction uses a combination of Quaternary geologic mapping, historical ground-water information, and subsurface geotechnical data. The process for zoning earthquake-induced landslides incorporates earthquake loading, existing landslide features, slope gradient, rock strength, and geologic structure. Probabilistic seismic hazard maps, which are the underpinning for delineating seismic hazard zones, have been prepared for peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years (Petersen and others, 1996) in accordance with the mapping criteria.

This report summarizes seismic hazard zone mapping for potentially liquefiable soils and earthquake-induced landslides in the San Leandro 7.5-Minute Quadrangle.

SECTION 1

LIQUEFACTION EVALUATION REPORT

Liquefaction Zones in the San Leandro 7.5-Minute Quadrangle, Alameda County, California

By
**Jacqueline D. J. Bott, Kevin B. Clahan, M. Elise Mattison,
Keith L. Knudsen and Wayne D. Haydon**

**California Department of Conservation
California Geological Survey**

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use seismic hazard zone maps developed by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within seismic hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is on the Internet at <http://gmw.consrv.ca.gov/shmp/SHMPsp117.asp>

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation

committee under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of liquefaction analysis, evaluation, and mitigation techniques (SCEC, 1999). This text is also on the Internet at: <http://www.scec.org/>

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the San Leandro 7.5-Minute Quadrangle. Section 2 (addressing earthquake-induced landslides) and Section 3 (addressing potential ground shaking), complete the report, which is one of a series that summarizes production of similar seismic hazard zone maps within the state (Smith, 1996). Zone maps covering the cities of Oakland and Piedmont were released as official maps in 1999 (DOC, 1999). With release of this new map and report, the remaining areas within Alameda County on the San Leandro Quadrangle have been mapped. The liquefaction zones of required investigation have been modified slightly, primarily because of the availability of new, more detailed Quaternary geologic mapping (Sowers, unpublished). Additionally, information on shallow ground water was obtained from the State Water Resources Control Board, data that were not used in the earlier zoning effort. Finally, the method of mapping the margins of the liquefaction zone of required investigation has been refined; the new method includes comparing the thickness of young (Holocene) deposits with the depth to ground water. Additional information on seismic hazards zone mapping in California is on CGS's Internet web page: <http://www.consrv.ca.gov/CGS/index.htm>

BACKGROUND

Liquefaction-induced ground failure historically has been a major cause of earthquake damage in northern California. During the 1989 Loma Prieta and 1906 San Francisco earthquakes, significant damage to roads, utility pipelines, buildings, and other structures in the San Francisco Bay Area was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 50 feet of the ground surface. These geological and ground water conditions are widespread in the San Francisco Bay Area, most notably in alluviated valley floodplains and around the margin of the bay. In addition, the potential for strong earthquake ground shaking is high because of the many nearby active faults. The combination of these factors constitutes a significant seismic hazard in the San Francisco Bay Area, including areas in the San Leandro Quadrangle.

METHODS SUMMARY

Characterization of liquefaction hazard presented in this report requires preparation of maps that delineate areas underlain by potentially liquefiable sediment. The following were collected or generated for this evaluation:

- Existing geologic maps were used to provide an accurate representation of the spatial distribution of Quaternary deposits in the study area. Geologic units that generally

are susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill

- Construction of shallow ground-water maps showing the historically highest known ground-water levels
- Quantitative analysis of geotechnical data to evaluate liquefaction potential of deposits
- Information on potential ground shaking intensity based on CGS probabilistic shaking maps

The data collected for this evaluation were processed into a series of geographic information system (GIS) layers using commercially available software. The liquefaction zone map was derived from a synthesis of these data and according to criteria adopted by the SMGB (DOC, 2000).

SCOPE AND LIMITATIONS

Evaluation for potentially liquefiable soils generally is confined to areas covered by Quaternary (less than about 1.6 million years) sedimentary deposits. Such areas within the San Leandro Quadrangle consist mainly of gently sloping alluvial fans, areas bordering larger streams and low-lying shoreline regions. CGS's liquefaction hazard evaluations are based on information on earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and ground-water depth, which is gathered from various sources. Although selection of data used in this evaluation was rigorous, the quality of the data used varies. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data obtained from outside sources.

Liquefaction zone maps are intended to prompt more detailed, site-specific geotechnical investigations, as required by the Act. As such, liquefaction zone maps identify areas where the potential for liquefaction is relatively high. They do not predict the amount or direction of liquefaction-related ground displacements, or the amount of damage to facilities that may result from liquefaction. Factors that control liquefaction-induced ground failure are the extent, depth, density, and thickness of liquefiable materials, depth to ground water, rate of drainage, slope gradient, proximity to free faces, and intensity and duration of ground shaking. These factors must be evaluated on a site-specific basis to assess the potential for ground failure at any given project site.

Information developed in the study is presented in two parts: physiographic, geologic, and hydrologic conditions in PART I, and liquefaction and zoning evaluations in PART II.

PART I

PHYSIOGRAPHY

Study Area Location and Physiography

The San Leandro 7.5-Minute Quadrangle covers approximately 60 square miles in Alameda and San Mateo counties. The boundary between Alameda and San Mateo counties crosses San Francisco Bay through the southwestern corner of the quadrangle. San Francisco Bay occupies about half of the San Leandro Quadrangle. Alameda County is in the northeastern half of the quadrangle. Parts of the cities of Oakland, Alameda, San Leandro and Hayward occupy about 90 percent of the onshore region. The remainder of the region includes the unincorporated community of San Lorenzo, which is within Alameda County.

Gently sloping alluviated plains and low-lying shoreline regions bordering the San Francisco Bay cover the majority of the onshore region. The alluvial plains slope southwestward toward the bay. The northeastern corner of the quadrangle is occupied by moderately to steeply sloping terrain of the East Bay Hills, which rises to an elevation just over 720 feet at the highest point. Major streams in the area are San Leandro Creek and San Lorenzo Creek, which flow approximately westward from the East Bay Hills into the bay. San Leandro Creek has been dammed in several places to form Upper San Leandro Reservoir and Lake Chabot, which are located to the north and east of the San Leandro Quadrangle, respectively. The Estudillo Canal flows across the alluvial plain between the two creeks and follows the path of a former creek (Sowers, 1997).

Most of the gently sloping alluvial plains within the San Leandro Quadrangle have been developed for residential and commercial uses except for some areas along the San Francisco Bay shoreline. A strip of land along the shoreline including the Bay Farm Island-Oakland International Airport peninsula has been reclaimed from the bay and is protected in places from tidal flooding by levees. In Hayward, salt-evaporation ponds have been developed to utilize the flat-lying marshy region along the bay margin. About half of the hillside region in the northeastern corner of the quadrangle has been developed for residential use. The Lake Chabot Municipal Golf Course also occupies part of the hilly region. Major highways in the map area are parallel Interstates 880 and 580, the latter of which follows the base of the hills. The Bay Area Rapid Transit also serves this region and is located between the two Interstate highways. The Oakland International Airport is located in the northwest quadrant and part of the Hayward Air Terminal is located in the southeast quadrant.

GEOLOGY

Bedrock and Surficial Geology

Geologic units that generally are susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. To evaluate the areal and vertical distribution of shallow Quaternary deposits and to provide information on subsurface geologic, lithologic and engineering properties of the units in the San Leandro Quadrangle, digital maps were obtained from the U.S. Geological Survey. These include unpublished Quaternary mapping by Janet M. Sowers and a published map of part of Alameda County (Graymer, 2000). These GIS maps were combined, with minor modifications along the bedrock/Quaternary contact, to form a single, 1:24,000-scale geologic map of the San Leandro Quadrangle. The distribution of Quaternary deposits on this map (summarized on Plate 1.1) was used in combination with other data, discussed below, to evaluate liquefaction susceptibility and develop the Seismic Hazard Zone Map.

Other geologic maps and reports were reviewed, including Trask and Rolston (1951), Radbruch (1959), Atwater and others (1977), Helley and others (1979), Rogers and Figuers (1992), Lienkamper (1992), Sloan (1992), Graymer and others (1996), Helley and Graymer (1997), and Knudsen and others (2000b). Limited field reconnaissance was conducted to confirm the location of geologic contacts, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units.

The Quaternary geologic mapping methods used by Sowers (unpublished) in her mapping of the San Leandro Quadrangle are the same as described by Knudsen and others (2000a). The methods consist of interpretation of topographic maps, aerial photographs, and soil surveys, as well as compiled published and unpublished geologic maps. The ages of deposits are estimated using landform shape, relative geomorphic position, cross-cutting relationships, superposition, depth and degree of surface dissection, and relative degree of soil-profile development. Table 1.1 compares stratigraphic nomenclature used in Knudsen and others (2000b) and the CGS GIS database, with that of several previous studies performed in northern California.

About half of the onshore region of the San Leandro Quadrangle is covered by Holocene alluvial fan and associated deposits. The other half is covered by either Holocene Bay Mud (Qhbm) or artificial fill overlying Bay Mud (afbm) along parts of the San Francisco Bay margin. Jurassic-Cretaceous bedrock is also exposed in the northeastern corner of the map. There are small bodies of engineered fill (af) underlying some freeways and train tracks. A small area of Quaternary dune sand (Qds) is exposed just northwest of the Oakland airport. Some artificial channels (ac) have been built along the lower reaches of the creeks.

The Holocene alluvial fan deposits have been subdivided into the following units: Qhc, Qhf, Qhff, Qhfy, Qhl and Qhly. Qhc are active stream-channel deposits mapped along the bed of San Leandro Creek. Qhl are branching levee deposits. Qhff are fine-grained fan deposits generally exposed at the distal parts of the fans. Qhfy are historically inundated fan deposits and are exposed where the two main creeks approach the bay.

UNIT	Knudsen and others (2000a)	Helley and Graymer (1997)	Helley and others (1979)	CGS GIS database
Artificial fill	af	af		af
Artificial fill over Bay Mud	afbm			afbm
Artificial fill, levee	alf	alf		alf
Artificial stream channel	ac	Qhasc		ac
Modern stream channel deposits	Qhc	Qhsc	Qhsc	Qhc
Latest Holocene alluvial fan deposits	Qhfy	Qhaf1		Qhfy
Latest Holocene alluvial fan levee deposits	Qhly			Qhly
Latest Holocene stream terrace deposits	Qhty	Qhfp1,2		Qhty
Holocene San Francisco Bay Mud	Qhbm	Qhbm	Qhbm	Qhbm
Holocene alluvial fan deposits	Qhf	Qhaf	Qham, Qhac	Qhf
Holocene alluvial fan deposits, fine facies	Qhff		Qhaf	Qhff
Holocene alluvial fan levee deposits	Qhl	Qhl		Qhl
Holocene stream terrace deposits	Qht	Qhfp		Qht
Holocene alluvium, undifferentiated	Qha	Qhaf		Qha
Latest Pleistocene to Holocene alluvial fan deposits ⁽¹⁾	Qf			Qf ⁽¹⁾
Latest Pleistocene to Holocene dune sand	Qds	Qms, Qhms	Qps	Qds
Latest Pleistocene alluvial fan deposits	Qpf	Qpaf		Qpf
Late Pleistocene San Francisco Bay Mud ⁽¹⁾				Qpbm ⁽¹⁾
Early to middle Pleistocene alluvial fan deposits ⁽¹⁾	Qof			Qof ⁽¹⁾
Pleistocene Irvington Gravels				QTi?

Notes:

(1) Not mapped at surface but unit interpreted in the subsurface.

Table 1.1. Correlation of Quaternary Stratigraphic Nomenclatures Used within the San Leandro Quadrangle. For this study, CGS has adopted the nomenclature of Knudsen and others (2000b).

Qhly are young levee deposits and are only mapped along San Lorenzo Creek close to the bay, and Qhf are undivided Holocene alluvial fan deposits. Within the East Bay Hills there are some small Holocene terrace deposits (Qht and Qhty) along San Leandro Creek, and some undivided Holocene and latest Pleistocene alluvium (Qha and Qpf). Some outcrops of unconsolidated gravels have been mapped as Pleistocene Irvington Gravels (QTi?) at elevations between 340 and 660 feet in the hills on the northeast side of the Hayward Fault (Graymer, 2000).

Bedrock exposed in the northeastern corner of San Leandro Quadrangle consists of fault slices of gabbro and pillow basalt of the Jurassic Coast Range Ophiolite (Jgb and Jpb), Late Jurassic-Early Cretaceous Franciscan rocks (KJfmw), Jurassic silicic volcanics (Jsv, quartz keratophyre) and Late Jurassic-Early Cretaceous Knoxville Formation (KJk, mostly shale with thin sandstone interbeds). See the Earthquake Induced Landslide portion (Section 2) of this report for additional description of the bedrock.

Structural Geology

The San Leandro Quadrangle is within the active San Andreas Fault system, which distributes shearing across a complex family of primarily northwest-trending, right-lateral, strike-slip faults that include the San Andreas, Hayward, and Calaveras faults. The active trace of the Hayward Fault passes through the northeastern corner of the San Leandro Quadrangle (Lienkamper, 1992) and is located within a narrow valley behind the base of the hills. However, the northernmost extent of surface rupture resulting from the October 21, 1868 Hayward earthquake (magnitude 6.8) was mapped by Radbruch-Hall, (1974) along the base of the hills south of San Leandro Creek, farther to the west than the mapped active trace of Lienkamper (1992).

ENGINEERING GEOLOGY

Information on subsurface geology and engineering characteristics of flatland deposits was obtained from borehole logs collected from reports on geotechnical and environmental projects. For this investigation, borehole logs were collected from the files of the City of San Leandro, City of Hayward, City of Oakland, City of Alameda and Alameda County. Data from 182 borehole logs were entered into a CGS geotechnical GIS database (Table 1.2). Forty of the logs were used in the earlier zoning of the portion of the City of Oakland within this quadrangle (DOC, 1999).

Standard Penetration Tests (SPTs) provide a standardized measure of the penetration resistance of geologic deposits and are commonly used as an index of soil density. This in-field test consists of counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil at the bottom of a borehole at chosen intervals while drilling. The driving force is provided by dropping a 140-pound hammer weight 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (ASTM, 1999). Recorded blow counts for non-SPT geotechnical sampling where the sampler diameter, hammer weight or drop distance differ from those specified for an SPT (ASTM D1586),

are converted to SPT-equivalent blow counts. The actual and converted SPT blow counts are normalized to a common-reference, effective-overburden pressure of one atmosphere (approximately one ton per square foot) and a hammer efficiency of 60 percent using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$.

Geotechnical and environmental borehole logs provided information on lithologic and engineering characteristics of Quaternary deposits within the study area. Geotechnical characteristics of the Quaternary map units are generalized in Table 1.2. Analysis of these data can be used to characterize and thus distinguish between units. These analyses reveal that: 1) Holocene materials are generally less dense and more readily penetrated than Pleistocene materials, especially the coarse-grained components; 2) latest Pleistocene alluvial fan deposits (Qpf) have higher dry density measurements than Holocene alluvial fan deposits (Qhf); 3) latest Pleistocene alluvial fan deposits (Qpf) contain more gravel and are coarser grained than Holocene alluvial fan deposits (Qhf); 4) Holocene alluvial units are predominantly fine grained, but have sand lenses throughout that have the potential to liquefy; 5) limited data for latest Pleistocene to Holocene dune sand (Qds) indicates that this map unit is generally dense; and 6) most units have a wide range in their dry density and penetration resistance.

GEOLOGIC MAP UNIT		DRY DENSITY (pounds per cubic foot)						STANDARD PENETRATION RESISTANCE (blows per foot, (N ₁) ₆₀)					
Unit (1)	Texture (2)	Number of Tests (3)	Mean	CV (4)	Median	Min	Max	Number of Tests (3)	Mean	CV (4)	Median	Min	Max
f	fine	14	112	0.07	111.0	101.0	126.0	35	25	0.99	20	10	9
	coars	13	102.7	0.12	103.1	78	124	56	29	1.66	18	10	9
Qhfy	Fine	4	101.0	0.13	105.0	83.0	111.0	7	25	0.50	26	9	45
	Coarse	2	95.0	-	-	-	-	2	18	-	-	-	-
Qhbi	fine	30	92.7	0.16	94.0	81.0	101.0	85	11	0.75	9	1	43
	coars	2	108.5	0.07	108.5	103.0	114.0	10	17	0.63	17	1	30
Qhf	Fine	143	99.8	0.08	101.0	72.0	116.5	305	16	0.60	14	3	87
	Coarse	30	104.4	0.08	106.0	73.0	118.0	103	19	0.72	16	3	83
Qhff	fine	1	-	-	-	-	-	13	17	0.46	17	1	35
	coars	0	-	-	-	-	-	1	-	-	-	-	-
Qhl	Fine	13	103.1	0.06	104.6	90.0	111.0	27	21	0.64	17	6	66
	Coarse	6	109.2	0.08	108.5	95.1	119.0	19	17	0.81	12	5	57
Qds	fine	0	-	-	-	-	-	0	-	-	-	-	-
	coars	0	-	-	-	-	-	5	37	0.31	35	1	55
Qf	Fine	8	105.8	0.05	106.5	96.5	112.2	13	14	0.47	12	7	31
	Coarse	1	-	-	-	-	-	11	17	0.58	13	9	38
Qpf	fine	89	104.6	0.06	105.8	88.8	116.0	87	21	0.69	16	1	55
	coars	70	115.8	0.09	115.6	102.0	138.0	49	28	0.60	26	1	55
Qpbi	fine	7	103.4	0.03	106.0	108.0	106.0	1	-	-	-	-	-
	coars	1	-	-	-	-	-	0	-	-	-	-	-

Notes:

- (1) See Table 1.3 for names of the geologic map units listed here.
- (2) Fine soils (silt and clay) contain a greater percentage passing the #200 sieve (<0.074 mm); coarse soils (sand and gravel) contain a greater percentage retained by the #200 sieve.
- (3) Number of laboratory samples or field penetration resistance measurements.
- (4) CV = coefficient of variation (standard deviation divided by the mean).

Table 1.2. Summary of Geotechnical Characteristics for Quaternary Geological Units in the San Leandro 7.5-Minute Quadrangle.

Geologic Map Unit (1)	Description	Length of boreholes penetrating map unit (feet)	Composition by Soil Type (2) (Percent of total sediment column logged)	Depth to ground water (feet) and liquefaction susceptibility category assigned to geologic unit (3)			
				<10	10 to 30	30 to 40	>40
af	Artificial fill (4)	639	L 25; SC 12; SM 12; M 7; Other 44	/H-I	H-L	M-L	VL
afbm	Artificial fill over Bay Mud	0	n/a (5)	VH	H	M	VL
alf	Artificial fill, levee	0	n/a	/H-I	H-L	M-L	VL
ac	Artificial stream channel	0	n/a	VH-L	H	M	VL
Qhc	Modern stream channel deposits	0	n/a	VH	H	M	VL
Qhfy	Latest Holocene alluvial fan deposits	36	CL 60; SC 13; CH12 Other 15	VH	H	M	VL
Qhly	Latest Holocene alluvial fan levee deposits	22	CL 42; ML 42; SM 16	VH	H	M	VL
Qhty	Latest Holocene stream terrace deposits	0	n/a	VH	H	M	VL
Qhbm	Holocene San Francisco Bay Mud	677	CL 55; CH 31; Other 14	H	M	L	VL
Qhf	Holocene alluvial fan deposits	2584	CL 55; ML 14; SM 10; Other 21	H	M	L	VL
Qhff	Holocene alluvial fan deposits, fir facies	99	CL 50; CH 43; Other 7	M	M	L	VL
Qhl	Holocene alluvial fan levee deposits	252	CL 42; SM 24; ML 15; Other 19	H	M	L	VL
Qht	Holocene stream terrace deposits	0	n/a	M	M	L	VL
Qha	Holocene alluvium, undifferentiated	0	n/a	M	M	L	VL
Qf	Latest Pleistocene to Holocene alluvial fan deposits	203	CL 56; SC 25; Other 19	M	L	L	VL
Qds	Latest Pleistocene to Holocene dune sand	74	SP 54; SC 20; CL 14; Other 12	M	L	L	VL
Qpf	Latest Pleistocene alluvial fan deposits	1827	CL 44; SM 15; SC 12; ML 11; Other 18	L	L	VL	VL
Qpbm	Late Pleistocene Bay Mud	141	CL 79; GP 11; Other 10	L	L	VL	VL
Qof	Early to middle Pleistocene alluvial fan deposits	34	CL 76; Other 24	L	L	VL	VL

Notes:

- (1) Susceptibility assignments are specific to the materials within the San Leandro 7.5-Minute Quadrangle.
- (2) Unified Soil Classification System.
- (3) Based on the Simplified Procedure (Seed and Idriss, 1971; Youd and Idriss, 1997) and a small number of borehole analyses for some units.
- (4) The liquefaction susceptibility of artificial fill ranges widely, depending largely on the nature of the fill, its age, and whether it was compacted during emplacement.
- (5) n/a = not applicable

Table 1.3. Liquefaction Susceptibility for Quaternary Map Units within the San Leandro 7.5-Minute Quadrangle. Units indicate relative susceptibility of deposits to liquefaction as a function of material type and ground-water depth within that deposit. VH = very high, H = high, M = moderate, L = low, and VL = very low to none.

GROUND WATER

Liquefaction hazard may exist in areas where depth to ground water is 50 feet or less. CGS uses the highest known ground-water levels because water levels during an earthquake cannot be anticipated because of the unpredictable fluctuations caused by natural processes and human activities. A historical-high ground-water map differs from most ground-water maps, which show the actual water table at a particular time. Plate 1.2 depicts a hypothetical ground-water table within alluviated areas.

Ground-water conditions were investigated in the San Leandro Quadrangle to evaluate the depth to saturated materials. Saturated conditions reduce the effective normal stress, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). The evaluation was based on first-encountered water noted in geotechnical borehole logs acquired from Alameda County Water District, the City of San Leandro, City of Oakland, City of Alameda, Alameda County and the State Water Resources Control Board. The depths to first-encountered unconfined ground water were plotted onto a map of the project area to constrain the estimate of historically shallowest ground water. Water depths from boreholes known to penetrate confined aquifers were not utilized.

Regional ground-water contours on Plate 1.2 show historically highest water depths, as interpreted from borehole logs from investigations between the 1950's and 1999. Depths to first-encountered water range from 0 to 35 feet below the ground surface (Plate 1.2). The ground-water levels are measured relative to the ground surface and so the surface topography should be taken into account when interpreting these data. In general, ground-water levels are shallowest close to the San Francisco Bay margin (Plate 1.2). Boreholes located north of San Lorenzo Creek indicate an area of elevated ground water on the central eastern edge of the quadrangle. Ground water is deepest (greater than 30 feet) near where San Leandro Creek exits from the East Bay Hills (Plate 1.2). However, this coincides with increased elevation of the ground surface toward the head of the fan and so the water table roughly parallels the ground surface.

PART II

LIQUEFACTION POTENTIAL

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. Liquefied sediment loses strength and may fail, causing damage to

buildings, bridges, and other structures. Many methods for mapping liquefaction hazard have been proposed. Youd (1991) highlights the principal developments and notes some of the widely used criteria. Youd and Perkins (1978) demonstrate the use of geologic criteria as a qualitative characterization of liquefaction susceptibility and introduce the mapping technique of combining a liquefaction susceptibility map and a liquefaction opportunity map to produce a liquefaction potential map. Liquefaction susceptibility is a function of the capacity of sediment to resist liquefaction. Liquefaction opportunity is a function of the potential seismic ground shaking intensity.

The method applied in this study for evaluating liquefaction potential is similar to that of Tinsley and others (1985). Tinsley and others (1985) applied a combination of the techniques used by Seed and others (1983) and Youd and Perkins (1978) for their mapping of liquefaction hazards in the Los Angeles region. CGS's method combines geotechnical analyses, geologic and hydrologic mapping, and probabilistic earthquake shaking estimates, but follows criteria adopted by the SMGB (DOC, 2000).

LIQUEFACTION SUSCEPTIBILITY

Liquefaction susceptibility reflects the relative resistance of a soil to loss of strength when subjected to ground shaking. Physical properties of soil such as sediment grain-size distribution, compaction, cementation, saturation, and depth govern the degree of resistance to liquefaction. Some of these properties can be correlated to a sediment's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment. Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not addressed in this investigation. Soil characteristics and processes that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. Thus, blow count and cone penetrometer values are useful indicators of liquefaction susceptibility.

Saturation is required for liquefaction, and the liquefaction susceptibility of a soil varies with the depth to ground water. Very shallow ground water increases the susceptibility to liquefaction (soil is more likely to liquefy). Soils that lack resistance (susceptible soils) typically are saturated, loose and sandy. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's map inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross-sections, geotechnical test data, geomorphology, and ground-water hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to ground water are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on similar soil observations, liquefaction susceptibility maps typically are similar to Quaternary geologic maps. CGS's qualitative

relations among susceptibility, geologic map unit and depth to ground water are summarized in Table 1.3.

For the San Leandro Quadrangle the Holocene and latest Pleistocene alluvial fan deposits generally have high clay content (Table 1.3) but also contain lenses of granular deposits, which can be loose in the Holocene deposits. Most Holocene materials with ground water within 30 feet of the ground surface, therefore, have been given susceptibility assignments of high (H) to very high (VH) (Table 1.3). Holocene alluvial fan fine-facies deposits (Qhff) primarily are composed of fine-grained material (over 90 percent clays) and have a correspondingly lower susceptibility assignment (M). Qht and Qha also have been assigned lower susceptibilities (M) for ground-water depths of less than 30 ft, and Qhbm, Qhf, and Qhl have high (H) to moderate (M) liquefaction susceptibilities. All latest Pleistocene and older deposits with ground water within 30 feet of the ground surface have low (L) susceptibility assignments except for latest Pleistocene to Holocene dune sand (Qds) which has been assigned moderate (M) to low (L) depending on ground-water depth. Artificial fill and latest Holocene alluvial fan, fan levee, stream and stream-terrace deposits have moderate (M) susceptibility assignments where they are saturated between 30 and 40 feet. All other units deeper than 30 feet from the ground surface have low (L) to (VL) susceptibility assignment. Artificial fill over Bay Mud (afbm) has been given a very high susceptibility where saturated as this geologic map unit has hosted about 50 percent of all historical occurrences of earthquake-induced liquefaction in the Bay Area (Knudsen and others, 2000b).

LIQUEFACTION OPPORTUNITY

Liquefaction opportunity is a measure, expressed in probabilistic terms, of the potential for strong ground shaking. Analyses of in-situ liquefaction resistance require assessment of liquefaction opportunity. The minimum level of seismic excitation to be used for such purposes is the level of peak ground acceleration (PGA) with a 10 percent probability of exceedance over a 50-year period (DOC, 2000). The earthquake magnitude used in CGS's analysis is the magnitude that contributes most to the calculated PGA for an area.

For the San Leandro Quadrangle, PGAs of 0.57 to 0.78 g, resulting from earthquakes of magnitude (M) 6.9 to 7.1, were used for liquefaction analyses. The PGA and magnitude values were based on de-aggregation of the probabilistic hazard at the 10 percent in 50-year hazard level (Petersen and others, 1996). See the ground-motion section (3) of this report for further details.

Quantitative Liquefaction Analysis

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997; Youd and others, 2001). Using the Seed-Idriss Simplified Procedure one can calculate soil resistance to liquefaction, expressed in terms of cyclic resistance ratio (CRR), based on SPT results, ground-water level, soil density, moisture content, soil

type, and sample depth. CRR values are then compared to calculated earthquake-generated shear stresses expressed in terms of cyclic stress ratio (CSR). The Seed-Idriss Simplified Procedure requires normalizing earthquake loading relative to a M7.5 event for the liquefaction analysis. To accomplish this, CGS's analysis uses the Idriss magnitude-scaling factor (MSF) (Youd and Idriss, 1997). It is convenient to think in terms of a factor of safety (FS) relative to liquefaction, where: $FS = (CRR / CSR) * MSF$. FS, therefore, is a quantitative measure of liquefaction potential. CGS uses a factor of safety of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil. While an FS of 1.0 is considered the "trigger" for liquefaction, for a site specific analysis an FS of as much as 1.5 may be appropriate depending on the vulnerability of the site and related structures.

The CGS liquefaction analysis program calculates an FS for each geotechnical sample where blow counts were collected. Typically, multiple samples are collected for each borehole. The program then independently calculates an FS for each non-clay layer that includes at least one penetration test using the minimum $(N_1)_{60}$ value for that layer. The minimum FS value of the layers penetrated by the borehole is used to determine the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data. FS, as well as other considerations such as slope, presence of free faces, and thickness and depth of potentially liquefiable soil, are evaluated in order to construct liquefaction potential maps, which are then used to make a map showing zones of required investigation.

Of the 182 geotechnical borehole logs reviewed in this study (Plate 1.2), 144 include blow-count data from SPTs or from penetration tests that allow reasonable blow count translations to SPT-equivalent values. Non-SPT values, such as those resulting from the use of 2-inch or 2½-inch inside-diameter ring samplers, were translated to SPT-equivalent values if reasonable factors could be used in conversion calculations. The reliability of the SPT-equivalent values varies. Therefore, they are weighted and used in a more qualitative manner. Few borehole logs, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or using averaged test values of similar materials.

The Seed-Idriss Simplified Procedure for liquefaction evaluation was developed primarily for clean sand and silty sand. As described above, results depend greatly on accurate evaluation of in-situ soil density as measured by the number of soil penetration blow counts using an SPT sampler. However, many of the Holocene alluvial deposits in the study area contain a significant amount of gravel. In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and recent laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995). SPT-derived density measurements in gravelly soils are unreliable and generally too high. They are likely to lead to overestimation of

the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N values appear to have been affected by gravel content, correlations were made with boreholes in the same unit where the N values do not appear to have been affected by gravel content.

LIQUEFACTION ZONES

Criteria for Zoning

Areas underlain by materials susceptible to liquefaction during an earthquake were included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (DOC, 2000). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following:

1. Areas known to have experienced liquefaction during historical earthquakes
2. All areas of uncompacted artificial fill containing liquefaction-susceptible material that are saturated, nearly saturated, or may be expected to become saturated
3. Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable
4. Areas where existing geotechnical data are insufficient

In areas of limited or no geotechnical data, susceptibility zones may be identified by geologic criteria as follows:

- a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the $M_{7.5}$ -weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the water table is less than 40 feet below the ground surface; or
- b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the $M_{7.5}$ -weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the historical high water table is less than or equal to 30 feet below the ground surface; or
- c) Areas containing soil deposits of latest Pleistocene age (11,000 to 15,000 years), where the $M_{7.5}$ -weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the historical high water table is less than or equal to 20 feet below the ground surface.

Application of SMGB criteria to liquefaction zoning in the San Leandro Quadrangle is summarized below.

Areas of Past Liquefaction

Knudsen and others (2000b) compiled data from Tinsley and others (1998) and Youd and Hoose (1978) for earthquakes in the San Francisco Bay region. Tinsley and others (1998) compiled observations of evidence for liquefaction for the 1989 Loma Prieta earthquake. Youd and Hoose (1978) compiled them for earlier earthquakes, including 1868 Hayward and 1906 San Francisco earthquakes. The Knudsen and others (2000b) digital database differs from earlier compilation efforts in that the observations were located on a 1:24,000-scale base map versus the smaller-scale base maps used in the earlier publications. Sites were reevaluated and some single sites were broken into two or more where the greater base-map scale allowed. Within the San Leandro Quadrangle, Tinsley and others (1998) identified three liquefaction sites from the 1989 Loma Prieta earthquake (Plate 1.2). Bay Farm Island hosted numerous liquefaction effects including minor pavement cracks and pipeline breaks. Sand boils and fissures occurred along a half-mile stretch of South Loop Road and Harbor Bay Parkway (site 48). Sand boils, pavement cracking, and lateral spreading occurred at the Oakland International Airport (sites 49 and 50) on the northern third of the main jet runway and adjacent taxiway. More deformation was sustained northwest of that runway. Settlement and lateral spreading on the perimeter dike were on the order of 1.5 feet. In the southern part of the airport, about 6 feet of sand and water filled an underground tramway, pavement settled near the main terminals, and a pipeline broke on Sally Ride Road, north of the terminals. Youd and Hoose (1978) cite information documenting surface cracks on Bay Farm Island following the 1906 earthquake (site 174, Plate 1.2), and cracks and boils at site 172 following the 1868 earthquake. The latter also resulted in reports of volumes of water flowing in previously dry San Leandro Creek and an unnamed creek, which had been nearly dry (Youd and Hoose, 1978).

Artificial Fills

In the San Leandro Quadrangle, artificial fill covers large areas along the margin of San Francisco Bay including the Oakland airport on the Bay Farm Island peninsula. These artificial fills generally overlie young Bay Mud (Qhbm) and have experienced historical liquefaction, as described above. Several episodes of artificial fill emplacement have been identified at the Oakland International airport. The most significant expansion occurred between 1939 and 1958 (William Lettis and Associates, 1999), and boreholes reveal both loose and dense fill materials in the subsurface. All areas of artificial fill over Bay Mud (afbm) are included in the zone of required investigation. Bay Mud has hosted about 50 percent of all reported historical liquefaction for earthquakes in the San Francisco Bay area (Knudsen and others, 2000a). Other artificial fills that show at the scale of mapping consist of engineered fill for river levees, elevated freeways and train tracks. Since these fills are considered to be properly engineered, zoning for liquefaction in these areas depends on soil conditions in the underlying strata.

Areas with Sufficient Existing Geotechnical Data

Borehole logs that include penetration test data and sufficiently detailed lithologic descriptions were used to evaluate liquefaction potential. These areas with sufficient

geotechnical data were evaluated for zoning based on the liquefaction potential determined by the Seed-Idriss Simplified Procedure. In Holocene alluvial deposits that cover much of the San Leandro Quadrangle, most of the borehole logs that were analyzed using the Seed-Idriss Simplified Procedure contain sediment layers that may liquefy under the expected earthquake loading. These areas containing saturated potentially liquefiable material are included in the zone.

Based on geologic interpretation of the thickness of Holocene alluvial fan deposits across the San Leandro Creek alluvial fan and shallow ground water, most of the flatlands within the San Leandro Quadrangle are within the liquefaction zone of required investigation. The edge of the zone south of San Leandro Creek was defined where the top of Pleistocene fan deposits are saturated but overlying Holocene deposits are not saturated. Pleistocene alluvial fan deposits are interpreted to be less susceptible to liquefaction than Holocene deposits when saturated, being more dense and compacted (Tables 1.2 and 1.3). Areas where depth to the top of the Pleistocene deposits is less than the depth to the highest historical ground water (thus, Holocene deposits are not saturated) were not included in the zone of required investigation. Only a narrow strip along the base of the hills about 0.3 mile wide is not included in the zone for this reason. There are thick saturated Holocene alluvial fan deposits that may contain liquefiable materials west of the zone boundary. Many boreholes in this region were found to contain potentially liquefiable material.

Areas with Insufficient Existing Geotechnical Data

To the north of San Leandro Creek near the base of the hills there is inadequate geotechnical borehole information to characterize the thickness and nature of the Holocene fan deposits. This region is critical for defining the boundary of the zone using the intersection of the top of Pleistocene with depth to historical high ground water. However, within the Oakland East Quadrangle, north of the San Leandro Quadrangle, geotechnical borehole information was adequate to characterize the thickness of Holocene alluvial fan deposits and this analysis was projected southward to this area. The zone is defined by the intersection of the projected top of Pleistocene and estimated historical high ground water depths, and then follows an inflection in the topography along an historical creek (Sowers, 1997) towards the base of the hills north of San Leandro Creek. The zone thus includes some boreholes located along the base of the hills north of San Leandro Creek, which have been determined to contain potentially liquefiable deposits. Again a strip about 0.3 mile wide, parallel to the base of the hills, is outside of the zone, where Holocene deposits are apparently not saturated.

Undifferentiated Holocene alluvium (Qha) and Holocene terrace and channel deposits (Qht, Qhc) could not be characterized adequately from available geotechnical data. These deposits were included within the zone for reasons presented in criterion 4. In the San Leandro Quadrangle ground water and forecast ground motions are sufficiently high to include these Holocene units within the liquefaction zone. These deposits are mapped along the upland part of San Leandro Creek and are likely to contain loose, granular, late Holocene material that is saturated because of the proximity to the active stream channel.

The latest Pleistocene to Holocene dune sand (Qds) that crops out on Bay Farm Island could not be adequately characterized based on the limited borehole information (Table 1.2). This unit was conservatively included in the zone, despite being dense, because this unit contains young saturated sandy deposits, which may have experienced historical liquefaction during the 1906 earthquake (Youd and Hoose, 1978).

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SECTION 2

EARTHQUAKE-INDUCED LANDSLIDE EVALUATION REPORT

Earthquake-Induced Landslide Zones in the San Leandro 7.5-Minute Quadrangle, Alameda County, California

By

**Timothy P. McCrink, Jacqueline D. J. Bott, Mark O. Wiegers, Rick I.
Wilson, Jack R. McMillan, and Wayne D. Haydon**

**California Department of Conservation
California Geological Survey**

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use seismic hazard zone maps prepared by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997). The text of this report is on the Internet at <http://gmw.consrv.ca.gov/shmp/SHMPsp117.asp>

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing landslide hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee in 1998 under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of landslide analysis, evaluation, and mitigation techniques (SCEC, 2002). This text is also on the Internet at: <http://www.scec.org/>

This section of the evaluation report summarizes seismic hazard zone mapping for earthquake-induced landslides in the San Leandro 7.5-Minute Quadrangle. Section 1 (addressing liquefaction) and Section 3 (addressing earthquake shaking), complete the report, which is one of a series that summarizes the preparation of seismic hazard zone maps within the state (Smith, 1996). Additional information on seismic hazard zone mapping in California can be accessed on the California Geological Survey's Internet page: <http://www.consrv.ca.gov/CGS/index.htm>

BACKGROUND

Landslides triggered by earthquakes historically have been a significant cause of earthquake damage. In California, large earthquakes such as the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes triggered landslides that were responsible for destroying or damaging numerous structures, blocking major transportation corridors, and damaging life-line infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, areas underlain by loose, weak soils, and areas on or adjacent to existing landslide deposits. These geologic and terrain conditions exist in many parts of California, including numerous hillside areas that have already been developed or are likely to be developed in the future. The opportunity for strong earthquake ground shaking is high in many parts of California because of the presence of numerous active faults. The combination of these factors constitutes a significant seismic hazard throughout much of California, including the hillside areas of the San Leandro Quadrangle.

METHODS SUMMARY

The mapping of earthquake-induced landslide hazard zones presented in this report is based on the best available terrain, geologic, geotechnical, and seismological data. If unavailable or significantly outdated, new forms of these data were compiled or generated specifically for this project. The following were collected or generated for this evaluation:

- Digital terrain data were used to provide an up-to-date representation of slope gradient and slope aspect in the study area
- Geologic mapping was used to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether triggered by earthquakes or not, was prepared
- Geotechnical laboratory test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area
- Seismological data in the form of CGS probabilistic shaking maps and catalogs of strong-motion records were used to characterize future earthquake shaking within the mapped area

The data collected for this evaluation were processed into a series of GIS layers using commercially available software. A slope stability analysis was performed using the Newmark method of analysis (Newmark, 1965), resulting in a map of landslide hazard potential. The earthquake-induced landslide hazard zone was derived from the landslide hazard potential map according to criteria developed in a CGS pilot study (McCrink and Real, 1996; McCrink, 2001) and adopted by the State Mining and Geology Board (DOC, 2000).

SCOPE AND LIMITATIONS

The methodology used to make this map is based on earthquake ground-shaking estimates, geologic material-strength characteristics and slope gradient. These data are gathered from a variety of outside sources. Although the selection of data used in this evaluation was rigorous, the quality of the data is variable. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data gathered from outside sources.

Earthquake-induced landslide zone maps are intended to prompt more detailed, site-specific geotechnical investigations as required by the Act. As such, these zone maps identify areas where the potential for earthquake-induced landslides is relatively high. Due to limitations in methodology, it should be noted that these zone maps do not necessarily capture all potential earthquake-induced landslide hazards. Earthquake-induced ground failures that are not addressed by this map include those associated with ridge-top spreading and shattered ridges. It should also be noted that no attempt has been made to map potential run-out areas of triggered landslides. It is possible that such run-out areas may extend beyond the zone boundaries. The potential for ground failure resulting from liquefaction-induced lateral spreading of alluvial materials, considered by some to be a form of landsliding, is not specifically addressed by the earthquake-induced landslide zone or this report. See Section 1, Liquefaction Evaluation Report for the San Leandro Quadrangle, for more information on the delineation of liquefaction zones.

Official Seismic Hazard Zone maps covering the City of Oakland, including the northernmost portion of the San Leandro Quadrangle, were released in March 2000 (DOC, 1999). This new map and report are the result of evaluation of seismic hazards within the rest of Alameda County land in the San Leandro Quadrangle. The landslide zones of required investigation within the City of Oakland have not changed as a result of this study. However, landslide zones have been identified in the adjacent City of San Leandro and unincorporated Alameda County.

The remainder of this report describes in more detail the mapping data and processes used to prepare the earthquake-induced landslide zone map for the San Leandro Quadrangle. The information is presented in two parts. Part I covers physiographic, geologic and engineering geologic conditions in the study area. Part II covers the preparation of landslide hazard potential and landslide zone maps.

PART I

PHYSIOGRAPHY

Study Area Location and Physiography

The San Leandro 7.5-Minute Quadrangle covers approximately 60 square miles in Alameda and San Mateo counties. The boundary between Alameda and San Mateo counties crosses the San Francisco Bay through the southwestern corner of the quadrangle. San Francisco Bay occupies about half of the San Leandro Quadrangle; the northeastern half of the quadrangle is within Alameda County. Parts of the cities of Oakland, Alameda, San Leandro and Hayward occupy about 90 percent of this region. The remainder includes San Lorenzo, which is part of unincorporated Alameda County.

Gently sloping alluviated plains and low-lying shoreline regions bordering the San Francisco Bay comprise most of the onshore region. The northeastern corner of the quadrangle (< 5 percent by area) is occupied by moderately to steeply sloping terrain of the East Bay Hills, rising to an elevation just over 720 feet at the highest point. Major streams in the area are San Leandro Creek and San Lorenzo Creek. San Leandro Creek flows along a steep ravine through the hills below Lake Chabot, which is located just to the east of San Leandro Quadrangle. Several short, steep ravines have been cut perpendicular to the trace of the Hayward Fault, which forms a small linear valley parallel to the base of the hills, but 1 km to the east.

Most of the gently sloping alluvial plains within the San Leandro Quadrangle have been developed for residential and commercial uses except for some areas along the margin of San Francisco Bay. Over half of the hillside region in the northeast corner of the quadrangle has been developed for residential use. The hillside terrain within the City of San Leandro has been modified significantly by cut and fill for residential development. The Lake Chabot Municipal Golf Course also occupies part of the hilltop area, north of San Leandro Creek. Parts of Lake Chabot Park and Knowland State Arboretum and Park

occupy small areas within the hilly region. Some of the steep, locally heavily wooded, hillside terrain on the northeastern side of the Hayward Fault has remained undeveloped. Major highways in the map area are Interstate highways 880 and 580.

Digital Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. An accurate slope gradient calculation begins with an up-to-date map representation of the earth's surface in the form of a digital topographic map. Within the San Leandro Quadrangle, a Level 2 digital elevation model (DEM) was obtained from the USGS (U.S. Geological Survey, 1993). This DEM, prepared from the 7.5-minute quadrangle topographic contours based on 1947 aerial photography, has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy.

Most of the hilly portions of the San Leandro Quadrangle were updated to reflect topography more accurate and more up-to-date than the USGS DEM. Within the City of Oakland, a set of digital terrain files were obtained from the city containing digitized contours, breaklines, and spot elevations that were collected from stereo-pair aerial photography flown in 1994. Terrain data in the form of digital contours were also obtained from the City of San Leandro. The San Leandro data were derived from 1:480-scale aerial photography flown in 1997. The files were translated into a format usable by CGS by first converting to a triangular-irregular-network (TIN) computer model. The TIN models were then converted into a regularly spaced digital elevation model (DEM). To complete the DEM in relatively flat-lying areas and areas not covered by the new terrain data, the Oakland and San Leandro DEM data were merged with the older USGS DEM. The resulting merged DEM has a 10-meter horizontal resolution. Vertical accuracy is estimated to be on the order of 1 to 2 meters within the City of Oakland, less than a meter in the City of San Leandro and 5 to 7.5 meters where the USGS DEM was applied. The area where the newer terrain data were applied is shown on Plate 2.1.

A slope map was made from the DEM using a third-order, finite difference, center-weighted algorithm (Horn, 1981). The DEM was also used to make a slope aspect map. The manner in which the slope and aspect maps were used to prepare the zone map will be described in subsequent sections of this report.

GEOLOGY

Bedrock and Surficial Geology

The primary source of bedrock geologic mapping used in this slope stability evaluation was a digital geologic map of Alameda County (Graymer, 2000). This map was merged with unpublished surficial Quaternary mapping by J.M. Sowers to form a single 1:24,000-scale geologic map. CGS geologists modified the digitized geologic map in the following ways. Contacts between bedrock and surficial units were revised to better conform to the topographic contours of the U.S. Geological Survey 7.5-minute quadrangle. Air-photo interpretation and field reconnaissance were performed to assist in adjusting contacts between bedrock and surficial geologic units and to review lithology of

geologic units and geologic structure. Surficial geology is discussed in more detail in Section 1 of this report.

The following description of bedrock geology is based mainly on the work of Graymer (2000). Bedrock located in the northeastern corner of the San Leandro Quadrangle consists of two highly deformed Mesozoic rock complexes: Late Jurassic to Late Cretaceous Franciscan Complex and the Late Jurassic and Early Cretaceous Great Valley Complex. The Great Valley Complex is further divided into Coast Range Ophiolite, composed mostly of serpentinite, gabbro, diabase, basalt and keratophyre, and Great Valley sequence, composed of sandstone, conglomerate and shale.

The oldest geologic units mapped in the San Leandro Quadrangle are igneous rocks from the Jurassic Coast Range Ophiolite and include mainly gabbro (Jgb) with minor amounts of pillow basalt and brecciated basalt (Jpb). Although not shown on the geologic map, some sheared serpentinite was observed in cut slopes in the City of San Leandro. Other Great Valley Complex rocks in the San Leandro Quadrangle include fault slices of Late Jurassic and Early Cretaceous Knoxville Formation (KJk) and Late Jurassic keratophyre and quartz keratophyre (Jsv). The Knoxville Formation (KJk) is a dark, greenish-gray silt or clay shale with thin sandstone interbeds (Graymer, 2000). The keratophyre (Jsv) consists of highly altered silicic volcanic rocks, remnants of a volcanic arc, which, although previously mapped as Tertiary Leona Rhyolite, recent isotopic and biostratigraphic analyses have shown to be of Jurassic age (Graymer, 2000). Undivided Franciscan Complex sandstone (KJfs; graywacke and meta-graywacke) is mapped in the northeastern corner of the quadrangle.

The oldest Quaternary deposits in the San Leandro Quadrangle are mapped by Graymer (2000) as possible Pleistocene and Pliocene Irvington Gravels (QTi?) of Savage (1951). These gravel deposits are found at elevations between 340 and 660 ft east of the Hayward Fault, and are poorly consolidated. They are thought to have been moved northwards and uplifted along the Hayward Fault based on interpretation of the main exposures of this unit, which are found in Fremont (Graymer, 2000).

Pleistocene to Holocene surficial units rest unconformably upon the bedrock units and consist of alluvial fan deposits (Qpf, Qha, Qhf, Qhl, Qhff, Qhfy, Qhly), fine-grained estuarine deposits (Qhbm), minor non-marine stream channel and terrace deposits (Qhc and Qht) and dune sand (Qds). A more detailed discussion of the Quaternary units can be found in Section 1.

Structural Geology

The bedrock structure in the East Bay hills reflects a complex deformational history. Deformation included Mesozoic and early Tertiary subduction and accretion, early to mid-Tertiary uplift, and finally, a period of strike-slip and reverse faulting that began in the late Miocene and continues to the present.

The primary structure in the study area is the Hayward Fault, an active right-lateral strike-slip fault with an estimated slip rate of about 9mm per year. The Hayward Fault is

actively creeping in Berkeley and other East Bay cities, as manifested by offset curbs, streets, buildings and other structures in numerous locations. The total slip on the Hayward Fault is estimated to be about 95 kilometers (Graymer, 2000). Lienkaemper (1992) has mapped the recently active trace of the Hayward Fault in detail. Additional traces are shown on earlier geologic maps (Smith, 1980; Radbruch-Hall, 1974). Associated with the main trace are numerous splays and subsidiary traces, which may accommodate secondary movements during events on the main trace, or which may be slightly older, abandoned traces. Bedrock units in the vicinity of the Hayward Fault zone have been complexly offset and juxtaposed along the main trace and its associated subsidiary traces.

The active trace of the Hayward Fault passes through the northeastern corner of the San Leandro Quadrangle (Lienkaemper, 1992) and is located within a narrow valley behind the base of the hills. However, the northernmost extent of surface rupture from the October 21, 1868 Hayward earthquake (magnitude 6.8) is shown by Radbruch-Hall (1974) along the base of the hills south of San Leandro Creek, farther to the west than the mapped active trace of Lienkaemper (1992). Fault traces to the west of the mapped active trace of the Hayward Fault also appear to have offset small pieces of Irvington Gravel deposits (QTi?) to varying elevations (340-600 ft), indicating that these subsidiary traces also have been active during the Quaternary.

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the San Leandro Quadrangle was prepared by field reconnaissance, analysis of stereo-paired aerial photographs and a review of previously published landslide mapping. Landslides were mapped at a scale of 1:24,000. For each landslide included on the map a number of characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable and questionable) and other properties, such as activity, thickness, and associated geologic unit(s). Landslides rated as definite and probable were carried into the slope stability analysis. Landslides rated as questionable were not carried into the slope stability analysis due to the uncertainty of their existence. The completed landslide map was scanned, digitized, and the attributes were compiled in a database. A version of this landslide inventory is included with Plate 2.1.

The distribution of landslides mapped for this study differs significantly from the distribution of landslides mapped by Nilsen (1975). Many more landslides were identified in this study, which also includes reported historical landslides. Landslides in the portion of the San Leandro Quadrangle within the boundaries of the City of Oakland were previously identified in the seismic hazard evaluation report for the City of Oakland (DOC, 1999). In this report, the hilly region within the City of San Leandro, south of San Leandro Creek was mapped, and any additional landslides identified were added to the Oakland inventory to complete the quadrangle.

Within the San Leandro Quadrangle, the majority of landslides occur on slopes underlain by gabbro of the Coast Range Ophiolite (Jgb) and the Late Jurassic siliceous volcanics (Jsv). Some smaller historical landslides occur in slopes underlain by Franciscan meta-

graywacke (KJfs) and artificial fill. Landslides in the area range from minor artificial fill failures, to shallow earth flows and deeper rotational rock slides; over half of which have occurred on southwest-facing slopes. Most of the additional landslides mapped within the city of San Leandro occurred since the 1960's, probably as a result of the failure of cut and fill modifications to the hillside terrain as it was developed for residential use. Landslides identified in the map area are shown on Plate 2.1.

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above were ranked and grouped on the basis of their shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. Shear-strength data for the units identified on the San Leandro Quadrangle geologic map were obtained from the City of San Leandro, the City of Oakland and Alameda County (see Appendix A). The locations of rock and soil samples taken for shear testing within the San Leandro Quadrangle are shown on Plate 2.1

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped on the basis of average angle of internal friction (average phi) and lithologic character. Average (mean or median) phi values for each geologic map unit and corresponding strength group are summarized in Table 2.1. For most of the geologic strength groups in the map area, a single shear strength value was assigned and used in our slope stability analysis. A geologic material strength map was made based on the groupings presented in Tables 2.1 and 2.2, and this map provides a spatial representation of material strength for use in the slope stability analysis.

Only a few bedrock units underlie the hilly northeastern corner of the San Leandro Quadrangle, namely: KJfmw, KJk, Jsv, Jpb and Jgb. For the first four units, because no new shear strength information was found, the strength groupings developed for the City of Oakland zone map (DOC, 1999) were applied in the San Leandro Quadrangle. Jgb (Jurassic gabbro) underlies almost all of the hilly terrain in the City of San Leandro and a significant number of new shear strength tests were obtained from several detailed geotechnical reports prepared in response to two notable recent landslides. These reports indicate that where Jgb is deeply weathered or where it is sheared along traces of the Hayward Fault, the shear strength is significantly diminished. In the absence of a map indicating the distribution of either deep weathering or shearing of Jgb, a lower shear strength value representing the average of all the tests within the City of San Leandro was developed and applied only within the City of San Leandro. This resulted in Jgb within the City of San Leandro dropping one strength group. The higher shear strength value developed for the City of Oakland was retained within the City of Oakland (see Table 2.1).

A number of new shear test values were obtained for Quaternary deposits within the City of San Leandro. These values were compared with correlative deposits from the City of Oakland zone map and found to conform to the groups previously established (DOC, 1999). Limited new information was found for Qhbm (Holocene Bay Mud) and Qhly (latest Holocene alluvial fan levee deposits) and these were assigned to existing groups on the basis of these tests.

Adverse Bedding Conditions

Adverse bedding conditions are an important consideration in slope stability analyses. Adverse bedding conditions occur where the dip direction of bedded sedimentary rocks is roughly the same as the slope aspect, and where the dip magnitude is less than the slope gradient. Under these conditions, landslides can slip along bedding surfaces due to a lack of lateral support.

To account for adverse bedding in our slope stability evaluation, we used geologic structural data in combination with digital terrain data to identify areas with potentially adverse bedding, using methods similar to those of Brabb (1983). The structural data, derived from the geologic map database, were used to categorize areas of common bedding dip direction and magnitude. The dip direction was then compared to the slope aspect and, if the same, the dip magnitude and slope gradient categories were compared. If the dip magnitude category was less than or equal to the slope gradient category, but greater than 25 percent (4:1 slope), the area was marked as a potential adverse bedding area.

Within the hilly portion of the San Leandro Quadrangle covered by the City of Oakland, the Knoxville Formation (KJj) and the undivided Franciscan Complex sandstone (KJfs) were found to have the stratigraphic and material strength characteristics conducive to adverse bedding conditions. These formations, which contain interbedded sandstone and shale, were subdivided based on shear strength differences between coarse-grained (higher strength) and fine-grained (lower strength) lithologies. Shear strength values for the fine- and coarse-grained lithologies were then applied to areas of favorable and adverse bedding orientation, which were determined from structural and terrain data as discussed above. It was assumed that coarse-grained material strength dominates where bedding dips into a slope (favorable bedding) while fine-grained material strength dominates where bedding dips out of a slope (adverse bedding). The geologic material strength map was modified by assigning the lower, fine-grained shear strength values to areas where potential adverse bedding conditions were identified. The favorable and adverse bedding shear strength parameters are included in Table 2.1.

Existing Landslides

As discussed later in this report, the criteria for landslide zone mapping state that all existing landslides that are mapped as definite or probable are automatically included in the landslide zone of required investigation. Therefore, an evaluation of shear strength parameters for existing landslides is not necessary for the preparation of the zone map. However, in the interest of completeness for the material strength map, to provide

relevant material strength information to project plan reviewers, and to allow for future revisions of our zone mapping procedures, we have collected and compiled shear strength data considered representative of existing landslides within the quadrangle.

The strength characteristics of existing landslides (Qls) must be based on tests of the materials along the landslide slip surface. Ideally, shear tests of slip surfaces formed in each mapped geologic unit would be used. However, this amount of information is rarely available, and for the preparation of the earthquake-induced landslide zone map it has been assumed that all landslides within the quadrangle have the same slip surface strength parameters. We collect and use primarily “residual” strength parameters from laboratory tests of slip surface materials tested in direct shear or ring shear test equipment. Back-calculated strength parameters, if the calculations appear to have been performed appropriately, have also been used.

Eleven direct shear tests of landslide slip surface materials were evaluated in preparing the City of Oakland zone map. In evaluating the San Leandro Quadrangle several additional reports were considered. These reports provided direct shear tests, ring shear tests, and back-calculated strength parameters for Jgb. All these new tests have either been performed on slip surface materials or the tests were designed to simulate the development of slip surfaces. These new values were combined with those previously compiled for the City of Oakland zone map to derive the value presented in Table 2.1.

SAN LEANDRO QUADRANGLE SHEAR STRENGTH GROUPS							
	Formation Name	Number Tests	Mean/Median Phi (deg)	Mean/Median Group Phi (deg)	Mean/Median Group C (psf)	No Data: Similar Lithology	Phi Values Used in Stability Analyses
GROUP 1	KJfs (fbc)	3	43/50*	41/41**	535/500**		41
GROUP 2	Jgb***	17	31/32*	33/33**	628/450**	KJk (fbc) Qhff, Qht	33
	Jsv	28	31/33*				
	Qhly	2	34.5/34.5				
GROUP 3	af	40	28/28.2*	28/27**	491/315**	ac, afbm, Qha, Qhfy, Qhc, Qhty, QTi?, Jpb	28
	Qhf	17	22.7/25				
	Qds	9	27/28*				
	Jgb****	18	28.2/29				
GROUP 4	Qhl	9	22/23*	23/22**	656/496**	alf	23
	Qpf	40	24.1/24*				
	KJfs (abc)	5	21/18*				
	KJk (abc)	7	24/26*				
GROUP 5	Qls	16	15.8/17*	15.8/17**	760/610**		16
	Qhbm	1	17				
* = Includes values derived from outside the San Leandro Quadrangle							
** = Group value includes shear data of geologic formations in the Oakland East Quadrangle that do not occur in the San Leandro Quadrangle and are not shown here.							
*** = Jgb within the City of Oakland							
**** = Jgb within the City of San Leandro							

Table 2.1. Summary of the Shear Strength Statistics for the San Leandro Quadrangle.

SHEAR STRENGTH GROUPS FOR THE SAN LEANDRO 7.5-MINUTE QUADRANGLE				
GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
KJfs (fbc)	Qhly, Qhff, Qht, KJk (fbc), Jgb***, Jsv	af, ac, afbm, Qha, , Qhc, Qhf, Qhfy, Qhty, Qds, QTi?, Jgb****, Jpb	alf, Qhl, Qpf, KJfs (abc), KJk (abc)	Qhbm, Qls

Table 2.2. Summary of Shear Strength Groups for the San Leandro Quadrangle.

PART II

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

Design Strong-Motion Record

The Newmark analysis used in delineating the earthquake-induced landslide zones requires the selection of a design earthquake strong-motion record. Because the active Hayward Fault traverses through the eastern area of the San Leandro Quadrangle, the selection of a strong motion record was based on the desire to match a large earthquake on the Hayward Fault. The Hayward Fault is a right-lateral strike-slip fault with a total length of approximately 86 km, and an estimated maximum moment magnitude of 7.1 (Petersen and others, 1996). The hilly areas of the eastern San Leandro Quadrangle, which would be susceptible to earthquake-induced landsliding, range from 0 km to about 2 km from the seismic source. Strong-motion records considered in the selection include: the CGS Strong Motion Instrumentation Program (SMIP) Corralitos record from the 1989 Loma Prieta earthquake; the Southern California Edison (SCE) Lucerne record from the 1992 Landers earthquake; and the Japan Meteorological Agency (JMA) Kobe City record from the 1995 Hyogoken-Nambu (Kobe) earthquake. The significant parameters for each of these earthquakes are listed below:

Strong-Motion Record	Moment Magnitude	Source to Site Distance (km)	PGA (g)
SMIP Corralitos	6.9	5.1	0.64
SCE Lucerne	7.3	1.1	0.80
JMA Kobe	6.9	0.6	0.82

The Corralitos record was eliminated because the fault motion was oblique, rather than purely strike-slip, and because of the relatively short rupture length. The Kobe record was eliminated because of uncertainties regarding the effects of topographic and basin-edge amplification at the recording site. Despite the slightly higher than expected magnitude, the Lucerne record from the 1992 Landers earthquake was used because it has many tectonic similarities to an earthquake on the Hayward Fault in the vicinity of the cities of San Leandro and Oakland.

The selected strong-motion record was not scaled or otherwise modified prior to analysis.

Displacement Calculation

The design strong-motion record was used to develop a relationship between landslide displacement and yield acceleration (a_y), defined as the earthquake horizontal ground acceleration above which landslide displacements take place. This relationship was prepared by integrating the design strong-motion record twice for a given acceleration value to find the corresponding displacement, and the process was repeated for a range of acceleration values (Jibson, 1993). The resulting curve in Figure 2.1 represents the full spectrum of displacements that can be expected for the design strong-motion record. This curve provides the required link between anticipated earthquake shaking and estimates of displacement for different combinations of geologic materials and slope gradient, as described in the Slope Stability Analysis section below.

The amount of displacement predicted by the Newmark analysis provides an indication of the relative amount of damage that could be caused by earthquake-induced landsliding. Displacements of 30, 15 and 5 cm were used as criteria for rating levels of earthquake-induced landslide hazard potential based on the work of Youd (1980), Wilson and Keefer (1983), and a CGS pilot study for earthquake-induced landslides (McCrink and Real, 1996; McCrink 2001). Applied to the curve in Figure 2.1, these displacements correspond to yield accelerations of 0.148, 0.182 and 0.243 g. Because these yield acceleration values are derived from the design strong-motion record, they represent the ground shaking opportunity thresholds that are significant in the San Leandro Quadrangle.

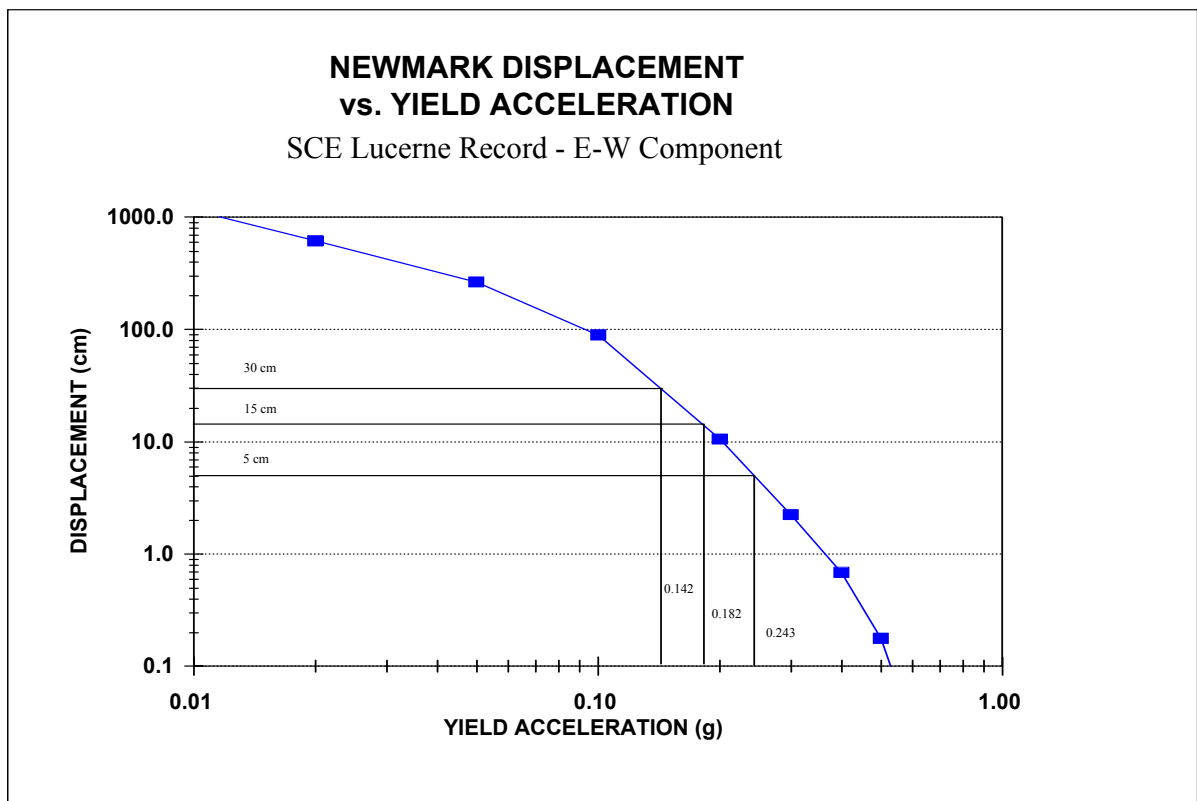


Figure 2.1. Yield Acceleration vs. Newmark Displacement for the Southern California Edison Lucerne strong-motion record from the 28 June 1992 Landers, California earthquake.

Slope Stability Analysis

A slope stability analysis was performed for each geologic material strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration from Newmark's equation:

$$a_y = (FS - 1)g \sin \alpha$$

where **FS** is the Factor of Safety, **g** is the acceleration due to gravity, and **α** is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite slope failure **α** is the same as the slope angle.

The yield accelerations resulting from Newmark's equations represent the susceptibility to earthquake-induced failure of each geologic material strength group for a range of slope gradients. Based on the relationship between yield acceleration and Newmark displacement shown in Figure 2.1, hazard potentials were assigned as follows:

1. If the calculated yield acceleration was less than 0.14 g, Newmark displacement greater than 30 cm is indicated, and a HIGH hazard potential was assigned
2. If the calculated yield acceleration fell between 0.14 g and 0.18 g, Newmark displacement between 15 cm and 30 cm is indicated, and a MODERATE hazard potential was assigned
3. If the calculated yield acceleration fell between 0.18 g and 0.24 g, Newmark displacement between 5 cm and 15 cm is indicated, and a LOW hazard potential was assigned
4. If the calculated yield acceleration was greater than 0.24 g, Newmark displacement of less than 5 cm is indicated, and a VERY LOW potential was assigned

Table 2.3 summarizes the results of the stability analyses in terms of slope gradients for each hazard potential level. The earthquake-induced landslide hazard potential map was prepared by combining the geologic material-strength map and the slope map according to this table.

SAN LEANDRO QUADRANGLE HAZARD POTENTIAL MATRIX				
Geologic Material Strength Group (Average Phi)	HAZARD POTENTIAL (Percent Slope)			
	Very Low	Low	Moderate	High
1 (41)	0 to 59%	60 to 65%	66 to 69%	70%+
2 (33)	0 to 38%	39 to 44%	45 to 49%	50%+
3 (28)	0 to 27%	28 to 33%	34 to 37%	38%+
4 (23)	0 to 18%	19 to 23%	24 to 27%	28%+
5 (16)	0 to 5%	6 to 10%	11 to 14%	15%+

Table 2.3. Hazard Potential Matrix for Earthquake-Induced Landslides in the San Leandro Quadrangle. Values in the table show the range of slope gradient (expressed as percent slope) corresponding to calculated Newmark displacement ranges from the design earthquake for each material strength group.

EARTHQUAKE-INDUCED LANDSLIDE HAZARD ZONE

Criteria for Zoning

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (DOC, 2000). Under these criteria, earthquake-induced landslide hazard zones are defined as areas that meet one or both of the following conditions:

1. Areas that have been identified as having experienced landslide movement in the past, including all mappable landslide deposits and source areas as well as any landslide that is known to have been triggered by historic earthquake activity.
2. Areas where the geologic and geotechnical data and analyses indicate that the earth materials may be susceptible to earthquake-induced slope failure.

These conditions are discussed in further detail in the following sections.

Existing Landslides

Existing landslides typically consist of disrupted soils and rock materials that are generally weaker than adjacent undisturbed rock and soil materials. Previous studies

indicate that existing landslides can be reactivated by earthquake movements (Keefer, 1984). Earthquake-triggered movement of existing landslides is most pronounced in steep head scarp areas and at the toe of existing landslide deposits. Although reactivation of deep-seated landslide deposits is less common (Keefer, 1984), a significant number of deep-seated landslide movements have occurred during, or soon after, several recent earthquakes. Based on these observations, all existing landslides with a definite or probable confidence rating are included within the earthquake-induced landslide hazard zone.

Geologic and Geotechnical Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink, 2001), it has been concluded that earthquake-induced landslide hazard zones should encompass all areas that have a High, Moderate or Low level of hazard potential (see Table 2.3). This would include all areas where the analyses indicate earthquake displacements of 5 centimeters or greater. Areas with a Very Low hazard potential, indicating less than 5 centimeters displacement, are excluded from the zone.

As summarized in Table 2.3, all areas characterized by the following geologic strength group and slope gradient conditions are included in the earthquake-induced landslide hazard zone:

1. Geologic Strength Group 5 is included in the earthquake-induced landslide zone for all slopes steeper than 5 percent.
2. Geologic Strength Group 4 is included for all slopes steeper than 18 percent.
3. Geologic Strength Group 3 is included for all slopes steeper than 27 percent.
4. Geologic Strength Group 2 is included for all slopes steeper than 38 percent.
5. Geologic Strength Group 1 is included for all slopes steeper than 59 percent.

This results in approximately two percent of the land area of the San Leandro Quadrangle covered by earthquake-induced landslide hazard zone. Stated another way, only about seven percent of the land area of the quadrangle has relief to be considered hilly, and about 24 percent of the hilly area is included in the landslide hazard zone for the San Leandro Quadrangle.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project. Johanna Overton and William Schock with the City of San Leandro, Gary Moore with the County of Alameda, and Norman Payne with the City of Hayward, and all the staff in the building, engineering and planning departments who arranged access and provided assistance in

retrieving geotechnical data from files maintained by the respective cities and county. Michael Hamer with the City of San Leandro provided digital topographic contours for updating the terrain. At CGS, Terilee McGuire, Lee Wallinder and Bob Moscovitz provided GIS support. Barbara Wanish prepared the DEM from the City of San Leandro terrain data. Elise Mattison, Anne Rosinski and Ross Martin prepared the plates. Barbara Wanish and Ross Martin prepared the final landslide hazard zone maps for this report.

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AIR PHOTOS

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APPENDIX A SOURCE OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City of San Leandro	40
City of Oakland	97
Alameda County	45
University of California	22
City of Berkeley	9
Lawrence Berkeley Laboratory	4
Cotton Shires Associates	4
Harza Engineering Company	9
Total Number of Shear Tests	230

SECTION 3

GROUND SHAKING EVALUATION REPORT

Potential Ground Shaking in the San Leandro 7.5-Minute Quadrangle, Alameda County, California

By

**Mark D. Petersen*, Chris H. Cramer*, Geoffrey A. Faneros,
Charles R. Real, and Michael S. Reichle**

**California Department of Conservation
California Geological Survey**

***Formerly with CGS, now with U.S. Geological Survey**

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the Seismic Hazard Zone Maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997). The text of this report is on the Internet at <http://gmw.consrv.ca.gov/shmp/SHMPsp117.asp>

This section of the evaluation report summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included are ground motion and related maps, a brief overview on how these maps were prepared, precautionary notes concerning their use, and related references. The maps provided

herein are presented at a scale of approximately 1:150,000 (scale bar provided on maps), and show the full 7.5-minute quadrangle and portions of the adjacent eight quadrangles. They can be used to assist in the specification of earthquake loading conditions *for the analysis of ground failure* according to the "Simple Prescribed Parameter Value" method (SPPV) described in the site investigation guidelines (California Department of Conservation, 1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard.

This section and Sections 1 and 2 (addressing liquefaction and earthquake-induced landslide hazards) constitute a report series that summarizes development of seismic hazard zone maps in the state. Additional information on seismic hazard zone mapping in California can be accessed on the California Geological Survey's Internet page: <http://www.consrv.ca.gov/CGS/index.htm>

EARTHQUAKE HAZARD MODEL

The estimated ground shaking is derived from the statewide probabilistic seismic hazard evaluation released cooperatively by the California Department of Conservation, Division of Mines and Geology [California Geological Survey], and the U.S. Geological Survey (Petersen and others, 1996). That report documents an extensive 3-year effort to obtain consensus within the scientific community regarding fault parameters that characterize the seismic hazard in California. Fault sources included in the model were evaluated for long-term slip rate, maximum earthquake magnitude, and rupture geometry. These fault parameters, along with historical seismicity, were used to estimate return times of moderate to large earthquakes that contribute to the hazard.

The ground shaking levels are estimated for each of the sources included in the seismic source model using attenuation relations that relate earthquake shaking with magnitude, distance from the earthquake, and type of fault rupture (strike-slip, reverse, normal, or subduction). The published hazard evaluation of Petersen and others (1996) only considers uniform firm-rock site conditions. In this report, however, we extend the hazard analysis to include the hazard of exceeding peak horizontal ground acceleration (PGA) at 10 percent probability of exceedance in 50 years on spatially uniform conditions of rock, soft rock, and alluvium. These soil and rock conditions approximately correspond to site categories defined in Chapter 16 of the Uniform Building Code (ICBO, 1997), which are commonly found in California. We use the attenuation relations of Boore and others (1997), Campbell (1997), Sadigh and others (1997), and Youngs and others (1997) to calculate the ground motions.

The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figures 3.1 through 3.3 show the hazard for PGA at 10 percent probability of exceedance in 50 years assuming the entire map area is firm rock, soft rock, or alluvial site conditions respectively. The sites where the hazard is calculated are represented as dots and ground motion contours as shaded regions. The quadrangle of interest is outlined by bold lines and centered on the map. Portions of the eight

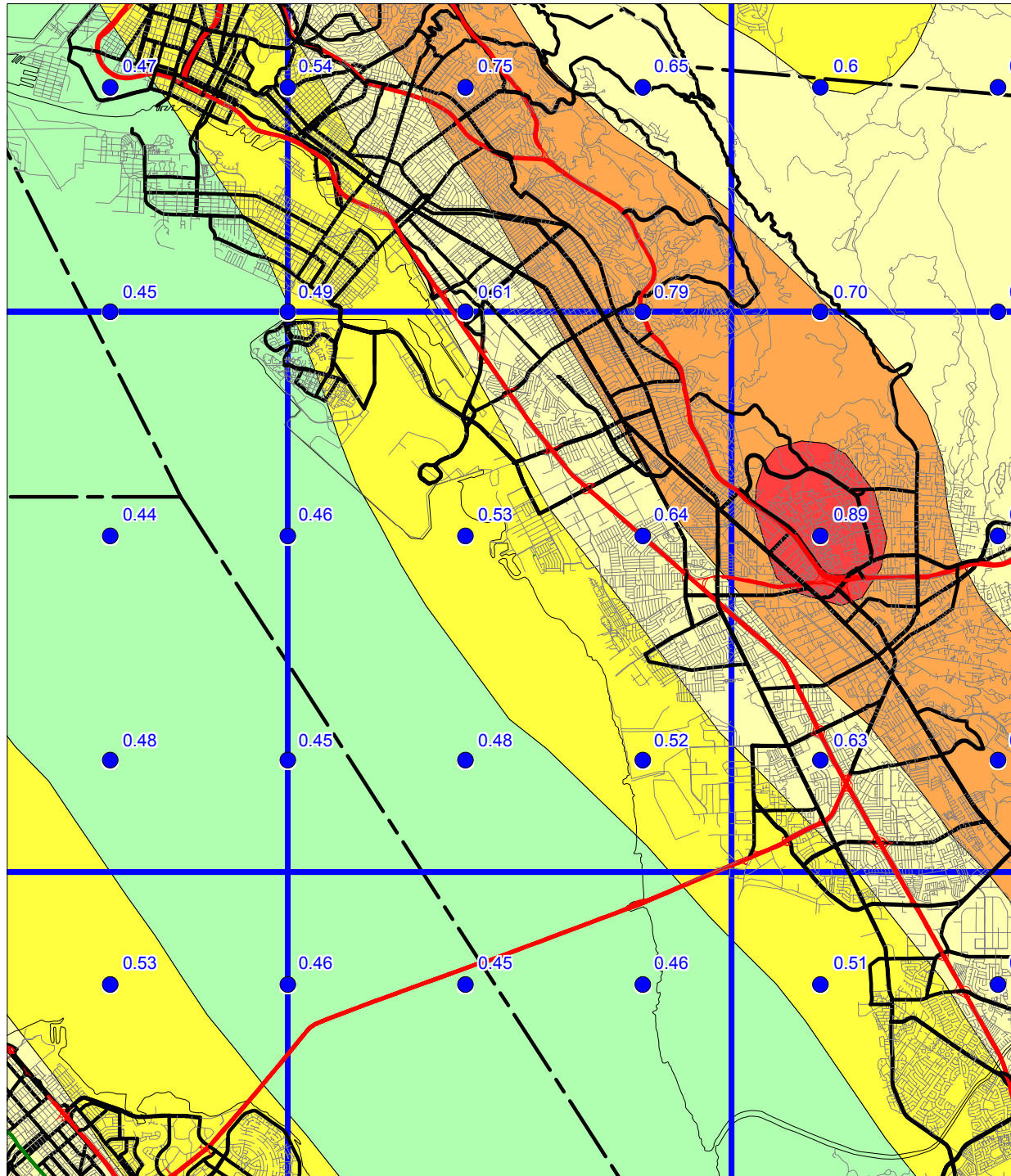
SEISMIC HAZARD EVALUATION OF THE SAN LEANDRO QUADRANGLE
SAN LEANDRO 7.5 MINUTE QUADRANGLE AND PORTIONS OF
ADJACENT QUADRANGLES

SHZR 078

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

FIRM ROCK CONDITIONS



Base map from GDT

0 1.5 3
Miles

Department of Conservation
California Geological Survey

Figure 3.1

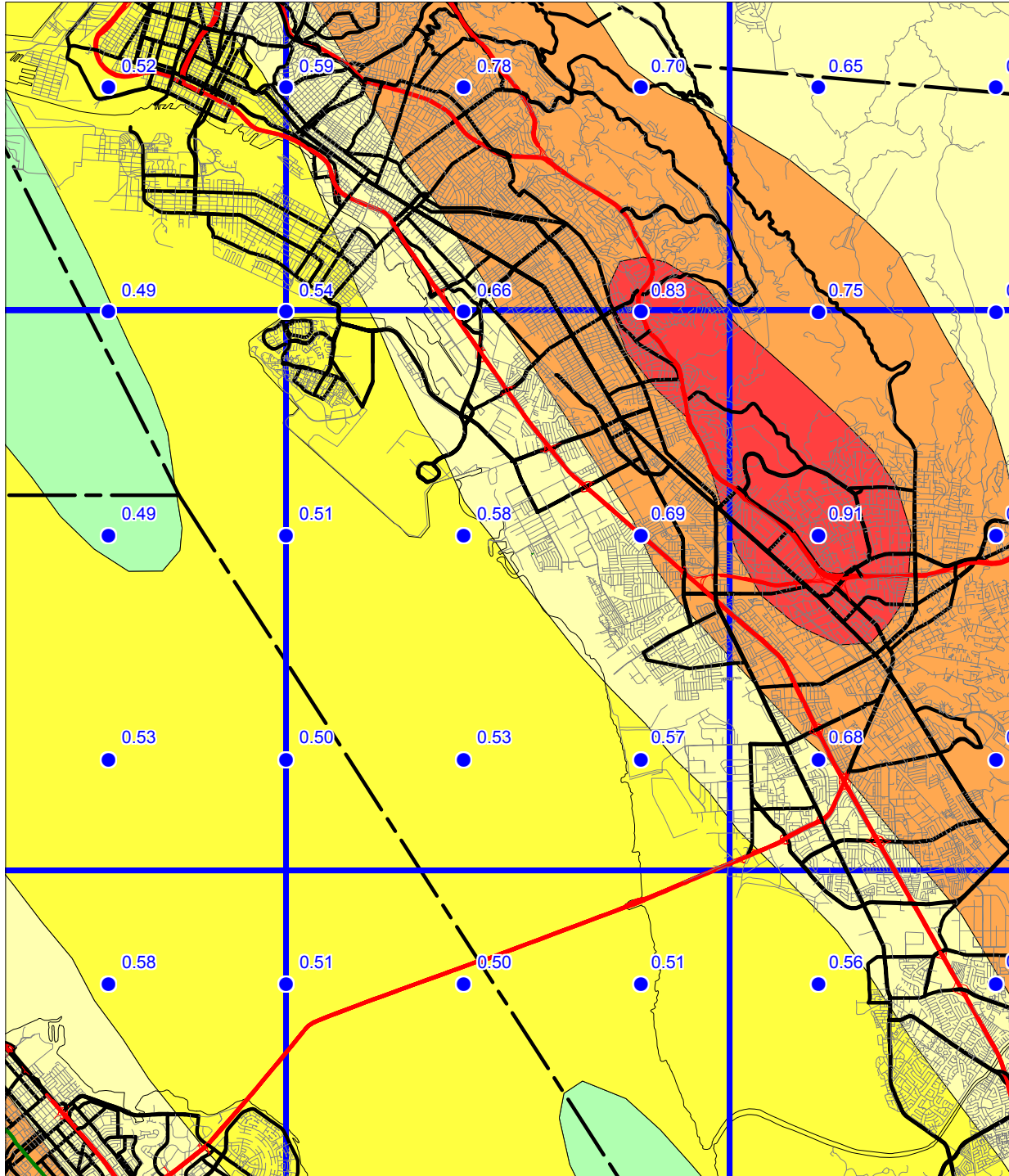


SEISMIC HAZARD EVALUATION OF THE RICHMOND QUADRANGLE
SAN LEANDRO 7.5 MINUTE QUADRANGLE AND PORTIONS OF
ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

SOFT ROCK CONDITIONS



Base map from GDT

0 1.5 3
Miles

Department of Conservation
California Geological Survey

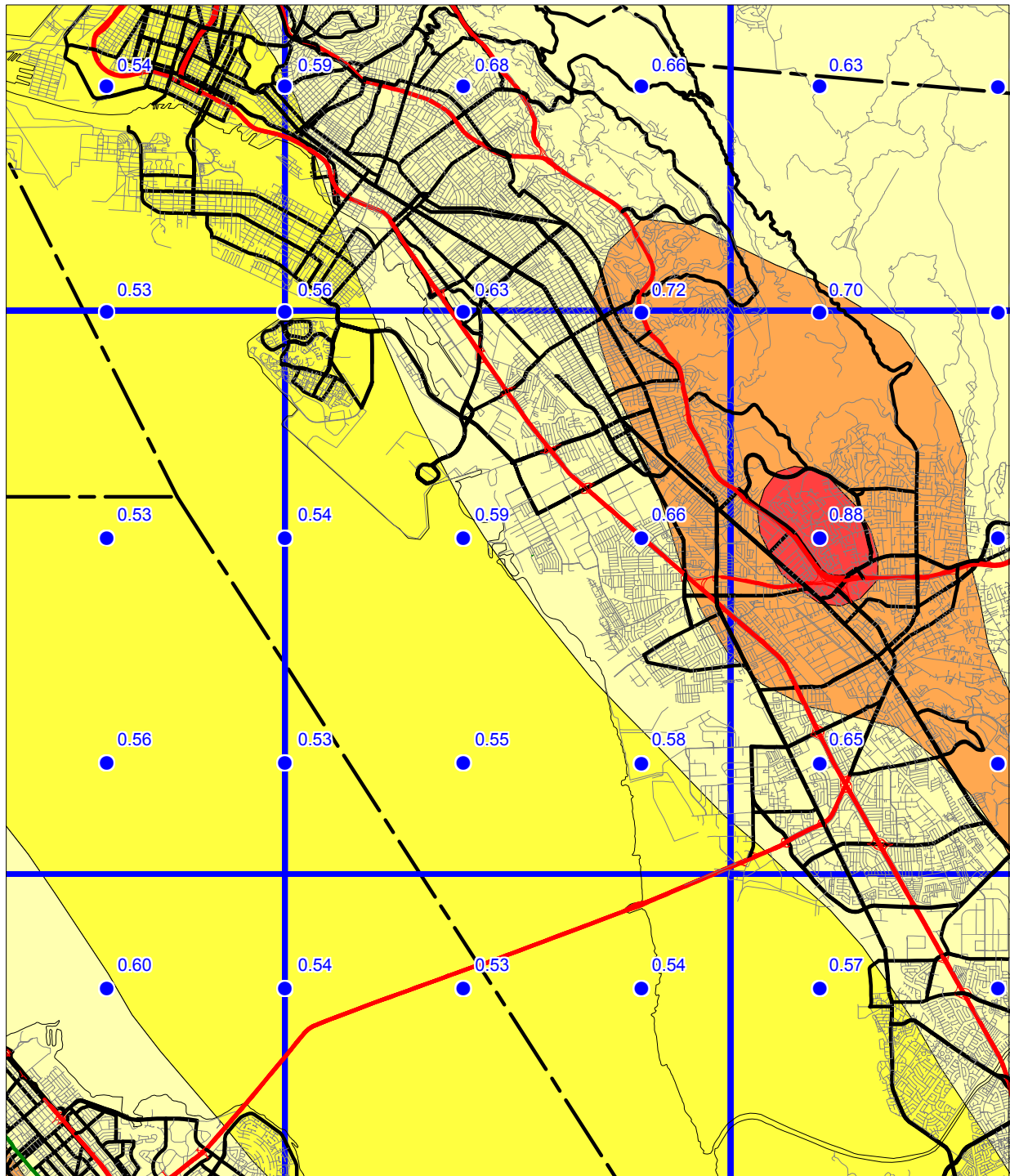
Figure 3.2



SAN LEANDRO 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)
1998

ALLUVIUM CONDITIONS



Base map from GDT

0 1.5 3
Miles

Department of Conservation
California Geological Survey



Figure 3.3

adjacent quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating ground motion values by selecting the map that matches the actual site conditions, and interpolating from the calculated values of PGA rather than the contours, since the points are more accurate.

APPLICATIONS FOR LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENTS

Deaggregation of the seismic hazard identifies the contribution of each of the earthquakes (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (see Cramer and Petersen, 1996). The map in Figure 3.4 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10 percent probability of exceedance in 50 years on alluvial site conditions (*predominant earthquake*). This information gives a rationale for selecting a seismic record or ground motion level in evaluating ground failure. However, it is important to keep in mind that more than one earthquake may contribute significantly to the hazard at a site, and those events can have markedly different magnitudes and distances. For liquefaction hazard the predominant earthquake magnitude from Figure 3.4 and PGA from Figure 3.3 (alluvium conditions) can be used with the Youd and Idriss (1997) approach to estimate cyclic stress ratio demand. For landslide hazard the predominant earthquake magnitude and distance can be used to select a seismic record that is consistent with the hazard for calculating the Newmark displacement (Wilson and Keefer, 1983). When selecting the predominant earthquake magnitude and distance, it is advisable to consider the range of values in the vicinity of the site and perform the ground failure analysis accordingly. This would yield a range in ground failure hazard from which recommendations appropriate to the specific project can be made. Grid values for predominant earthquake magnitude and distance should **not** be interpolated at the site location, because these parameters are not continuous functions.

A preferred method of using the probabilistic seismic hazard model and the “simplified Seed-Idriss method” of assessing liquefaction hazard is to apply magnitude scaling probabilistically while calculating peak ground acceleration for alluvium. The result is a “magnitude-weighted” ground motion (liquefaction opportunity) map that can be used directly in the calculation of the cyclic stress ratio threshold for liquefaction and for estimating the factor of safety against liquefaction (Youd and Idriss, 1997). This can provide a better estimate of liquefaction hazard than use of predominate magnitude described above, because all magnitudes contributing to the estimate are used to weight the probabilistic calculation of peak ground acceleration (Real and others, 2000). Thus, large distant earthquakes that occur less frequently but contribute *more* to the liquefaction hazard are appropriately accounted for.

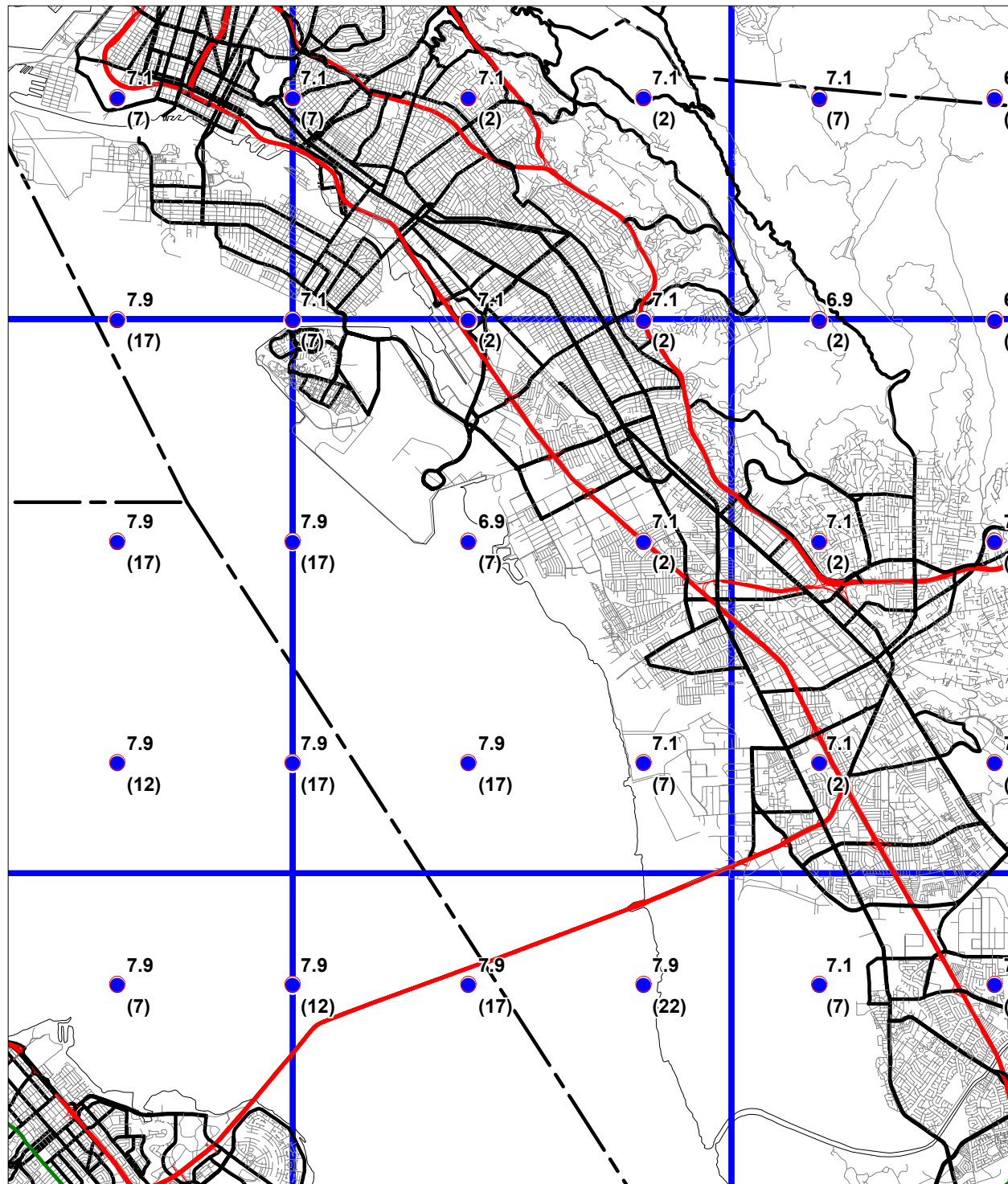
Figure 3.5 shows the magnitude-weighted alluvial PGA based on Idriss’ weighting function (Youd and Idriss, 1997). It is important to note that the values obtained from this map are pseudo-accelerations and should be used in the formula for factor of safety without any magnitude-scaling (a factor of 1) applied.

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION

1998

PREDOMINANT EARTHQUAKE

Magnitude (Mw)
(Distance (km))



Base map from GDT

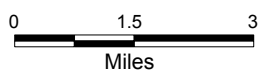
Department of Conservation
California Geological Survey

Figure 3.4

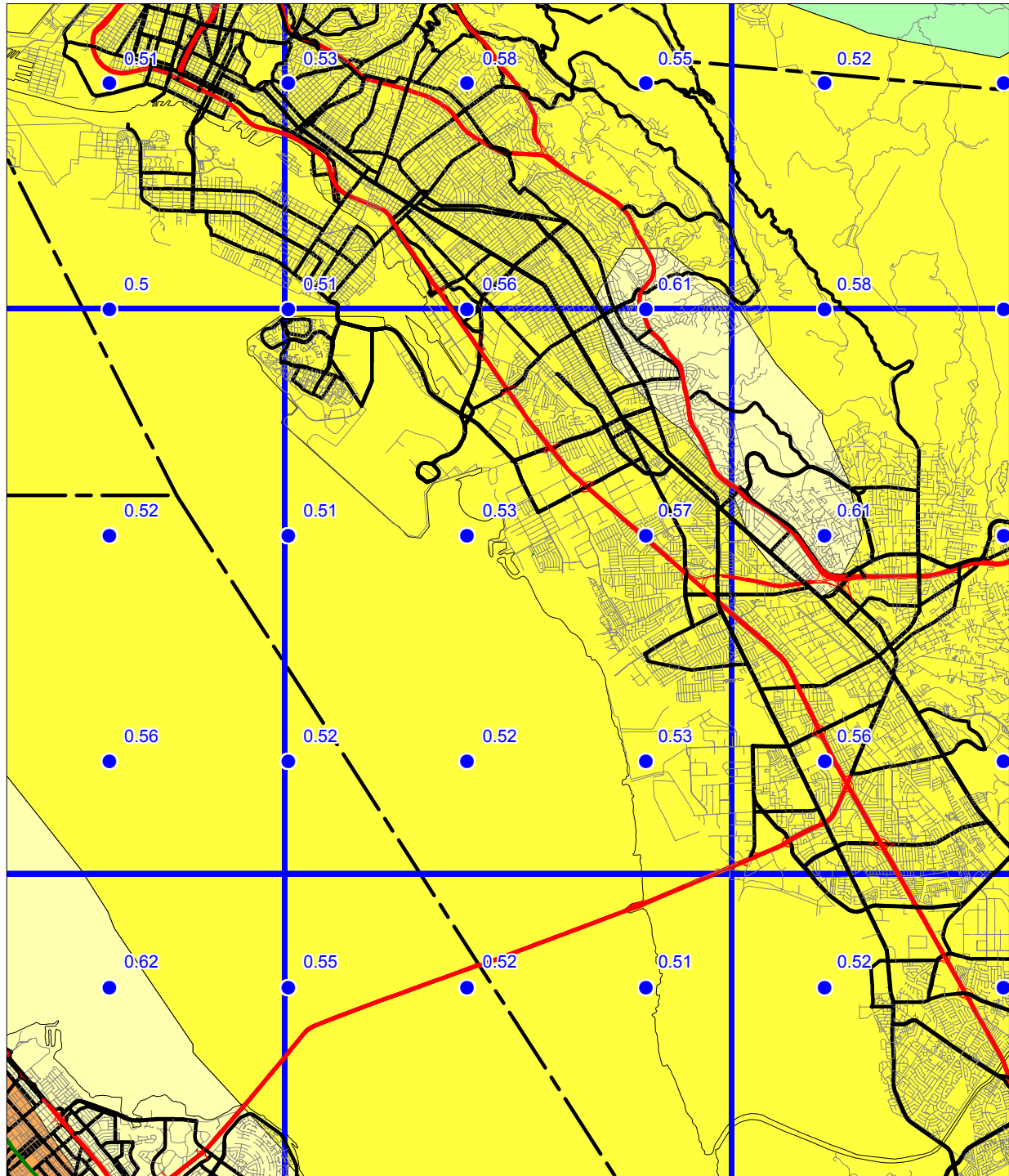


SEISMIC HAZARD EVALUATION OF THE SAN LEANDRO QUADRANGLE
SAN LEANDRO 7.5 MINUTE QUADRANGLE AND PORTIONS OF
ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS MAGNITUDE-WEIGHTED PSEUDO-PEAK ACCELERATION (g)
FOR ALLUVIUM

1998

LIQUEFACTION OPPORTUNITY



Base map from GDT

0 1.5 3
Miles

Department of Conservation
California Geological Survey

Figure 3.5



USE AND LIMITATIONS

The statewide map of seismic hazard has been developed using regional information and is *not appropriate for site specific structural design applications*. Use of the ground motion maps prepared at larger scale is limited to estimating earthquake loading conditions for preliminary assessment of ground failure at a specific location. We recommend consideration of site-specific analyses before deciding on the sole use of these maps for several reasons.

1. The seismogenic sources used to generate the peak ground accelerations were digitized from the 1:750,000-scale fault activity map of Jennings (1994). Uncertainties in fault location are estimated to be about 1 to 2 kilometers (Petersen and others, 1996). Therefore, differences in the location of calculated hazard values may also differ by a similar amount. At a specific location, however, the log-linear attenuation of ground motion with distance renders hazard estimates less sensitive to uncertainties in source location.
2. The hazard was calculated on a grid at sites separated by about 5 km (0.05 degrees). Therefore, the calculated hazard may be located a couple kilometers away from the site. We have provided shaded contours on the maps to indicate regional trends of the hazard model. However, the contours only show regional trends that may not be apparent from points on a single map. Differences of up to 2 km have been observed between contours and individual ground acceleration values. *We recommend that the user interpolate PGA between the grid point values rather than simply using the shaded contours.*
3. Uncertainties in the hazard values have been estimated to be about +/- 50 percent of the ground motion value at two standard deviations (Cramer and others, 1996).
4. Not all active faults in California are included in this model. For example, faults that do not have documented slip rates are not included in the source model. Scientific research may identify active faults that have not been previously recognized. Therefore, future versions of the hazard model may include other faults and omit faults that are currently considered.
5. A map of the predominant earthquake magnitude and distance is provided from the deaggregation of the probabilistic seismic hazard model. However, it is important to recognize that a site may have more than one earthquake that contributes significantly to the hazard. Therefore, in some cases earthquakes other than the predominant earthquake should also be considered.

Because of its simplicity, it is likely that the SPPV method (DOC, 1997) will be widely used to estimate earthquake shaking loading conditions for the evaluation of ground failure hazards. It should be kept in mind that ground motions at a given distance from an earthquake will vary depending on site-specific characteristics such as geology, soil properties, and topography, which may not have been adequately accounted for in the regional hazard analysis. Although this variance is represented to some degree by the

recorded ground motions that form the basis of the hazard model used to produce Figures 3.1, 3.2, and 3.3, extreme deviations can occur. More sophisticated methods that take into account other factors that may be present at the site (site amplification, basin effects, near source effects, etc.) should be employed as warranted. The decision to use the SPPV method with ground motions derived from Figures 3.1, 3.2, or 3.3 should be based on careful consideration of the above limitations, the geotechnical and seismological aspects of the project setting, and the “importance” or sensitivity of the proposed building with regard to occupant safety.

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SCALE

The scale bar consists of three horizontal segments. The top segment is labeled '1 MILE' at the right end and has tick marks at 0, .5, and 1. The middle segment is labeled '7000 FEET' at the right end and has tick marks at 1000, 2000, 3000, 4000, 5000, 6000, and 7000. The bottom segment is labeled '1 KILOMETER' at the right end and has tick marks at 0, .5, and 1.



B = Pre-Quaternary bedrock

See "Bedrock and Surficial Geology" in Section 1 of report for descriptions of units.



Plate 1.2 Historical liquefaction sites, depth to historically high ground water, and locations of boreholes used in this study, San Leandro 7.5-Minute Quadrangle, California

